

HAT-P-7: A RETROGRADE OR POLAR ORBIT, AND A THIRD BODY

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ABSTRACT

We show that the exoplanet HAT-P-7b has an extremely tilted orbit, with a true angle of at least 86° with respect to its parent star’s equatorial plane, and a strong possibility of retrograde motion. We also report evidence for an additional planet or companion star. The evidence for the unparalleled orbit and the third body is based on precise observations of the star’s apparent radial velocity (RV). The anomalous RV due to rotation (the Rossiter–McLaughlin effect) was found to be a blueshift during the first half of the transit and a redshift during the second half, an inversion of the usual pattern, implying that the angle between the sky-projected orbital and stellar angular momentum vectors is 182.5 ± 9.4 . The third body is implicated by excess RV variation of the host star over 2 yr. Some possible explanations for the tilted orbit of HAT-P-7b are a close encounter with another planet, the Kozai effect, and resonant capture by an inward-migrating outer planet.

Key words: planetary systems – planetary systems: formation – stars: individual (HAT-P-7) – stars: rotation

Online-only material: machine-readable table

1. INTRODUCTION

In the solar system, the planetary orbits are well aligned and prograde, revolving in the same direction as the rotation of the Sun. This fact inspired the “nebular hypothesis” that the Sun and planets formed from a single spinning disk (Laplace 1796). One might also expect exoplanetary orbits to be well aligned with their parent stars, and indeed this is true of most systems for which it has been possible to compare the directions of orbital motion and stellar rotation (Fabrycky & Winn 2009; Le Bouquin et al. 2009). However, there are at least three exoplanets for which the orbit is tilted by a larger angle than any of the planets in the solar system: XO-3b (Hébrard et al. 2008; Winn et al. 2009a), HD 80606b (Moutou et al. 2009; Pont et al. 2009; Winn et al. 2009b), and WASP-14b (Johnson et al. 2009).

Still, all of those systems are consistent with prograde orbits, with the largest minimum angle between the stellar-rotational and orbital angular momentum vectors of about 37° , for XO-3b (Winn et al. 2009a). The reason why only the *minimum* angle is known is that the evidence for misalignment is based on the eponymous effect of Rossiter (1924) and McLaughlin (1924), an anomalous Doppler shift observed during planetary transits that is sensitive only to the angle between the *sky projections* of the two vectors. The true spin–orbit angle may be larger, depending on the unknown inclination angle of the stellar rotation axis with respect to the line of sight.

In this Letter, we present evidence of a very large spin–orbit misalignment for HAT-P-7b, a planet of mass $1.8 M_{\text{Jup}}$ and radius $1.4 R_{\text{Jup}}$ in a 2.2-day orbit around an F6V star with mass $1.5 M_\odot$ and radius $1.8 R_\odot$ (Pál et al. 2008). We find the angle between the sky-projected angular momentum vectors to be 182.5 ± 9.4 . Furthermore, we show that the true angle ψ between those

vectors is likely greater than 86° , indicating that the orbit is either retrograde ($\psi > 90^\circ$) or nearly polar ($\psi \approx 90^\circ$). We also present evidence for a third body in the system, which may be an additional planet or a companion star. We present spectroscopic data in Section 2, photometric data in Section 3, a joint analysis of both types of data in Section 4, and a discussion of the results in Section 5.

2. RADIAL VELOCITIES

We observed HAT-P-7 with the High Resolution Spectrograph (HIRES) on the Keck I 10 m telescope, and the High Dispersion Spectrograph (HDS) on the Subaru 8 m telescope. The planet’s discoverers (Pál et al. 2008; hereafter P08) obtained eight HIRES spectra in 2007, to which we add nine spectra from 2009. All but one of the HIRES spectra were acquired outside of transits. Of the 49 HDS spectra, 9 were obtained on 2009 June 17 and 40 were obtained on 2009 July 1. The second of these nights spanned a transit.

The instrument settings and observing procedures in both 2007 and 2009 were identical to those used by the California Planet Search (CPS; Howard et al. 2009). We placed an iodine gas absorption cell into the optical path, to calibrate the instrumental response and wavelength scale. The radial velocity (RV) of each spectrum was measured with respect to an iodine-free template spectrum, using the algorithm of Butler et al. (2006) with subsequent improvements. Measurement errors were estimated from the scatter in the fits to individual spectral segments spanning a few angstroms. The RVs are given in Table 1.

2.1. Evidence for a Third Body

Figure 1 shows the RVs over the two-year span of the observations. Figure 2 shows the RVs as a function of orbital phase, fitted with two different models. The first model is a single

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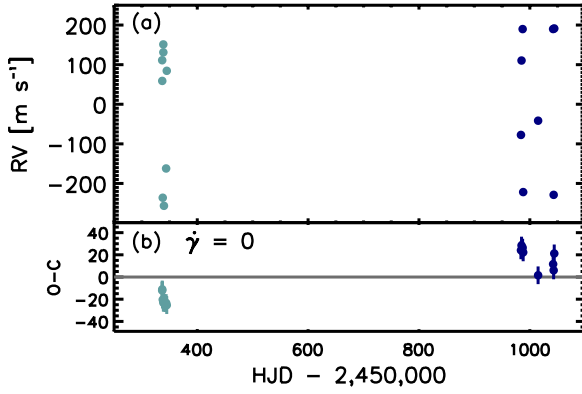


Figure 1. Long-term radial velocity variation of HAT-P-7. (a) Measured RVs. (b) Residuals (observed – calculated) between the data and the best-fitting single-planet model. Light blue and dark blue points are HRES data from 2007 and 2009, respectively.

Table 1
Relative Radial Velocity Measurements of HAT-P-7

HJD	RV (m s ⁻¹)	Error (m s ⁻¹)	Spectrograph ^a
2454336.73960	111.08	1.72	1
2454336.85367	58.89	1.78	1
2454337.76212	-236.06	1.70	1
2454338.77440	151.06	1.54	1
2454338.85456	131.12	1.57	1

Notes. The RV was measured relative to an arbitrary template spectrum specific to each spectrograph; only the differences among the RVs from a single spectrograph are significant. The uncertainty given in Column 3 is the internal error only and does not account for any possible “stellar jitter.”

^a (1) Keck/HIRES, (2) Subaru/HDS.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

Keplerian orbit, representing the signal of the known planet. The second model has an additional parameter $\dot{\gamma}$ representing an extra radial acceleration. The second model gives a better fit to the data, with a root-mean-squared (rms) residual of 7 m s⁻¹ as compared to 21 m s⁻¹ for the first model. The RVs from 2009 are systematically redshifted by approximately 40 m s⁻¹ compared to RVs from 2007, as evident from the residuals shown in Figures 1(b) and 2(b). This shift is highly significant, as the CPS has demonstrated a long-term stability of 2 m s⁻¹ or better using HIRES and the same reduction codes used here (Howard et al. 2009).

This RV trend is evidence for an additional companion. Given the limited time coverage of our observations (two clusters of points separated by 2 yr), the data are compatible with nearly any period longer than a few months. A constant acceleration is the simplest model that fits the excess RV variability, and under that assumption we may give an order-of-magnitude relation relating $\dot{\gamma}$ to some properties of the companion

$$\frac{M_c \sin i_c}{a_c^2} \sim \frac{\dot{\gamma}}{G} = (0.121 \pm 0.014) M_{\text{Jup}} \text{ AU}^{-2}, \quad (1)$$

where M_c is the companion mass, i_c its orbital inclination relative to the line of sight, a_c its orbital distance, and the numerical value is based on our model-fitting results (see Section 4).

2.2. Evidence for a Spin-orbit Misalignment

Figure 3(a) shows the RV data spanning the transit, after subtracting the orbital RV as computed with the best-fitting

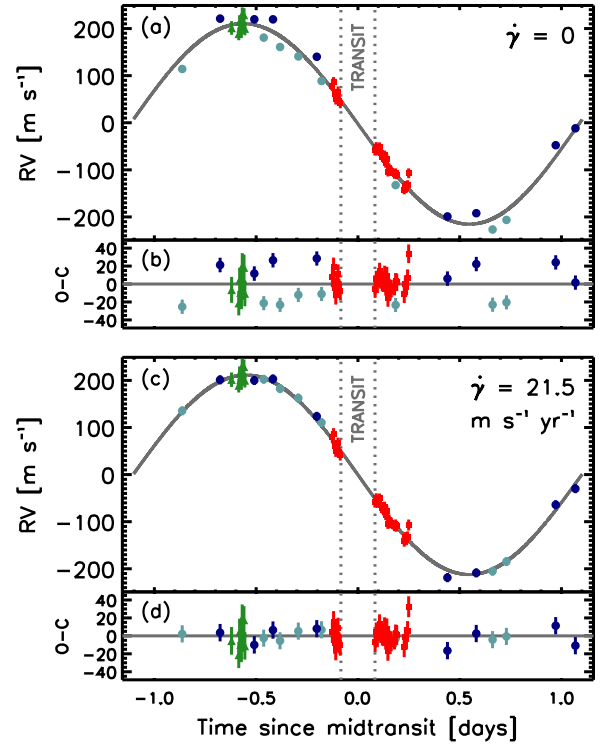


Figure 2. Phased radial velocity variation of HAT-P-7. (a) Assuming a single Keplerian orbit. (b) Residuals. (c) With an extra parameter $\dot{\gamma}$ representing a constant radial acceleration. (d) Residuals. The circles are HRES data (light blue from 2007, dark blue from 2009), the green triangles are HDS data from 2009 June 17, and the red squares are HDS data from 2009 July 1.

model including $\dot{\gamma}$. We interpret the “anomalous” RV variation during the transit as the Rossiter–McLaughlin (RM) effect, the asymmetry in the spectral lines due to the partial eclipse of the rotating photosphere. In the context of eclipsing binary stars, the RM effect was predicted by Holt (1893) and observed definitively by Rossiter (1924) and McLaughlin (1924). For exoplanets, the RM effect was first observed by Queloz et al. (2000), and its use in assessing spin-orbit alignment has been expounded by Ohta et al. (2005) and Gaudi & Winn (2007).

A transiting planet in a well-aligned prograde orbit would first pass in front of the blueshifted (approaching) half of the star, causing an anomalous redshift of the observed starlight. Then, the planet would cross to the redshifted (receding) half of the star, causing an anomalous blueshift. In contrast, Figure 3(a) shows a blueshift followed by a redshift: an inversion of the effect just described. We may conclude, even without any modeling, that the orbital “north pole” and the stellar “north pole” point in nearly opposite directions on the sky.

3. PHOTOMETRY

For a quantitative analysis of the RM effect, we wanted to model both the photometric and spectroscopic transit signals. For this purpose, we supplemented the RV data with the most precise transit light curve available to us, shown in Figure 3(c). This light curve is based on observations on UT 2008 September 22 in the Sloan *i* bandpass, with the Fred L. Whipple 1.2 m telescope and KeplerCam detector, under the auspices of the Transit Light Curve project (Holman et al. 2006; Winn et al. 2007).

Reduction of the CCD images involved standard procedures for bias subtraction and flat-field division. Differential aperture

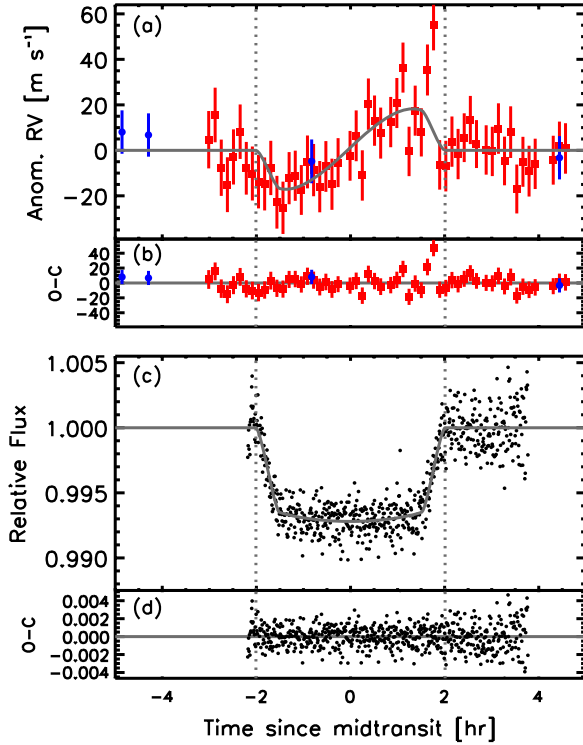


Figure 3. Spectroscopic and photometric transit of HAT-P-7b. (a) The anomalous RV, defined as the output of the Doppler code minus the orbital RV. We observed a blueshift in the first half of the transit, and a redshift in the second half of the transit, demonstrating that the sky projections of the orbital and stellar angular momentum vectors point in opposite directions. (b) Residuals. Red squares are HDS data from 2009 July 1, and blue circles are HRES data obtained on various nights in 2007 and 2009. (c) The relative flux, observed in the Sloan *i* band with the FLWO 1.2 m telescope and Keplercam. (d) Residuals. In panels (a) and (b), the gray line shows the best-fitting model.

photometry was performed for HAT-P-7 and seven comparison stars. No evidence was found for time-correlated noise using the “time-averaging” method of Pont et al. (2006), as implemented by Winn et al. (2009c). The data shown in Figure 3(c) were corrected for differential extinction as explained in Section 4.

4. JOINT ANALYSIS

We fitted a model to the photometric and RV data in order to derive quantitative constraints on the angle λ between the sky projections of the orbital and stellar-rotational angular momentum vectors. This angle is defined such that $\lambda = 0^\circ$ when the sky-projected vectors are parallel and $\lambda = 180^\circ$ when they are antiparallel. Our model for the RM effect was based on the technique of Winn et al. (2005): we simulated spectra exhibiting the RM effect at various transit phases, and then measured the apparent RV of the simulated spectra using the same Doppler code that is used on actual data. This allowed us to relate the anomalous RV to the parameters and positions of the star and planet.

The RV model was the sum of the Keplerian RV and the anomalous RV due to the RM effect. The photometric model was based on the analytic equation for the flux of a quadratically limb-darkened disk with a circular obstruction (Mandel & Agol 2002). As a compromise between fixing the limb-darkening coefficients u_1 and u_2 at theoretically calculated values, and giving them complete freedom, we fixed $u_1 - u_2$ at the tabulated value of 0.3846 (Claret 2004) and allowed $u_1 + u_2$ to be a free

Table 2
Model Parameters for HAT-P-7b

Parameter	Value
Orbital period, P (d)	2.2047304 ± 0.0000024
Midtransit time (HJD)	$2454,731.67929 \pm 0.00043$
Transit duration (first to fourth contact) (hr)	4.006 ± 0.064
Transit ingress or egress duration (hr)	$0.474^{+0.061}_{-0.093}$
Planet-to-star radius ratio, R_p/R_*	$0.0834^{+0.0012}_{-0.0021}$
Orbital inclination, i (deg)	$80.8^{+2.8}_{-1.2}$
Scaled semimajor axis, a/R_*	$3.82^{+0.39}_{-0.16}$
Transit impact parameter	$0.618^{+0.039}_{-0.149}$
Velocity semiamplitude, K (m s $^{-1}$)	211.8 ± 2.6
Upper limit on eccentricity (99.73% conf.)	0.039
$e \cos \omega$	-0.0019 ± 0.0077
$e \sin \omega$	0.0037 ± 0.0124
Velocity offset, Keck/HIRES (m s $^{-1}$)	-51.2 ± 3.6
Velocity offset, Subaru/HDS (m s $^{-1}$)	-4.8 ± 2.5
Constant radial acceleration $\dot{\gamma}$ (m s $^{-1}$ yr $^{-1}$)	21.5 ± 2.6
Projected stellar rotation rate, $v \sin i_*$ (km s $^{-1}$)	$4.9^{+1.2}_{-0.9}$
Projected spin-orbit angle, λ (deg)	182.5 ± 9.4

parameter. We also included a free parameter for the coefficient of differential air-mass extinction between HAT-P-7 and the ensemble of comparison stars.

We determined the best values of the model parameters and their 68.3% confidence limits using a Markov Chain Monte Carlo algorithm, as described in our previous works (see, e.g., Winn et al. 2009a). The likelihood function was given by $\exp(-\chi^2/2)$ with

$$\chi^2 = \sum_{i=1}^{N_f} \left[\frac{f_i(\text{obs}) - f_i(\text{calc})}{\sigma_{f,i}} \right]^2 + \sum_{i=1}^{N_v} \left[\frac{v_i(\text{obs}) - v_i(\text{calc})}{\sigma_{v,i}} \right]^2, \quad (2)$$

in a self-explanatory notation, with $\sigma_{f,i}$ chosen to be 0.00136, and $\sigma_{v,i}$ chosen to be the quadrature sum of the RV measurement error and a “stellar jitter” term of 9.3 m s $^{-1}$. These choices led to $\chi^2 = N_{\text{dof}}$ for the minimum- χ^2 model. A Gaussian prior constraint was imposed upon the orbital period based on the precise measurement of P08.

Table 2 gives the results for the model parameters. In particular, the result for λ is 182.5 ± 9.4 , close to antiparallel, as anticipated from the qualitative discussion of Section 2.

5. DISCUSSION

Our finding for λ is strongly suggestive of retrograde motion, in which the orbital motion and stellar rotation are in opposite directions. However, it must be remembered that λ refers to the angle between the *sky-projected* angular momentum vectors. The true angle ψ between the vectors is given by

$$\cos \psi = \cos i_* \cos i + \sin i_* \sin i \cos \lambda, \quad (3)$$

where i and i_* are the line-of-sight inclinations of the orbital and stellar angular momentum vectors, respectively. Although i is known precisely from the transit data, i_* is unknown.

Supposing i_* to be drawn from an “isotropic” distribution (uniform in $\cos i_*$), the data demand that $\psi > 86.3^\circ$ with 99.73% confidence. Thus, under this assumption, a retrograde orbit is strongly favored, although a nearly polar and barely prograde orbit cannot be ruled out.

In fact, there is circumstantial evidence that i_* is small and consequently the orbit of HAT-P-7b is nearly polar ($\psi \approx 90^\circ$). The star's projected rotation rate is unusually low for such a hot star: $v \sin i_* = 4.9^{+1.2}_{-0.9} \text{ km s}^{-1}$ in our model, or $3.8 \pm 0.5 \text{ km s}^{-1}$ based on the line profile analysis of P08, and $T_{\text{eff}} = 6350 \pm 80 \text{ K}$ according to P08. In the SPOCS catalog of dwarf stars with well-determined spectroscopic properties (Valenti & Fischer 2005), only 2 of 37 stars with $T_{\text{eff}} = 6350 \pm 100 \text{ K}$ have $v \sin i_* < 4.9 \text{ km s}^{-1}$.

Based on this catalog, the mean rotation rate v for such hot stars is about 15 km s^{-1} . As an alternate approach to constraining ψ , we assumed the rotation velocity v is drawn from a Gaussian distribution with mean 15 km s^{-1} and standard deviation 3 km s^{-1} . The result is $\psi = 94.6^{+5.5}_{-3.0} \text{ deg}$ with 68.3% confidence, and $\psi > 86.1$ with 99.73% confidence. This analysis favors nearly polar and retrograde orbits. However, one wonders whether HAT-P-7 should be expected to have a “typical” rotation rate, given the existence of its short-period planet on a bizarre orbit. Another caveat is that we found the scaled semimajor axis a/R_* to be about 1σ smaller than the finding of P08, suggesting the star is somewhat larger and more evolved, which would correspond to a slower expected rotation rate.

Determining i_* directly may be possible by measuring and interpreting asteroseismological oscillations (Gizon & Solanki 2003), or photometric modulations produced by starspots (see, e.g., Henry & Winn 2008). By good fortune, HAT-P-7 is in the field of view of the *Kepler* satellite, which is capable of precise long-term photometry and may be able to accomplish these tasks (Borucki et al. 2009).

The extraordinary orbit of HAT-P-7b presents an extreme case for theories of planet formation and subsequent orbital evolution. HAT-P-7b is a “hot Jupiter” and presumably migrated inward toward the star after its formation. A prevailing migration theory involves tidal interactions with the protoplanetary disk, but such interactions would probably not perturb the initial coplanarity of the system, and might even bring the system into closer alignment (Lubow & Ogilvie 2001; Cresswell et al. 2007). More promising to explain HAT-P-7b are scenarios involving few-body dynamics, as those scenarios are expected to produce misalignments. In one scenario, close encounters between planets throw a planet inward, where its orbit is ultimately shrunk and circularized by tidal dissipation (Chatterjee et al. 2008; Jurić & Tremaine 2008). Another idea is based on the Kozai (1962) effect, whereby the gravitational force from a distant body on a highly inclined orbit strongly modulates an inner planet's orbital eccentricity and inclination (Fabrycky & Tremaine 2007). Recent calculations showed that a combination of planet–planet scattering, the Kozai effect, and tidal friction can lead to nearly circular retrograde orbits (Nagasawa et al. 2008). A third proposed scenario involves an inward-migrating outer planet that captures an inner planet into a mean motion resonance; if the inner planet avoids being ejected or consumed by the star, it may be released on a nearly circular retrograde orbit (Yu & Tremaine 2001).

The prospect of explaining HAT-P-7b's orbit through few-body dynamics lends extra importance to measuring the mass and orbital parameters of the third body. If it turns out to be a planet, then HAT-P-7b will be only the second known case of a transiting planet accompanied by another planet, the first being HAT-P-13b (Bakos et al. 2009). Such systems are highly desirable because the unusually precise measurements enabled by transit observations can be used to determine whether the orbits are coplanar and give clues about the system's dynamical history (Fabrycky 2009).

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Note added after submission. Narita et al. (2009) report independent evidence for a retrograde or polar orbit of HAT-P-7b, based on Subaru/HDS spectra spanning the transit of 2008 May 30.

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